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Mixing in Stratified and Sediment-Laden Flows

Research Goals:
The long-range goal of our research program is to understand, using laboratory experiments, numerical modeling and theoretical analyses, the small-scale mixing processes that occur in oceanic stratified layers.

Objectives:
The objectives of research carried out during the past year were to: (i) understand entrainment processes across density interfaces subjected to differential turbulent forcing; and (ii) develop theoretical and laboratory-based descriptions for internal waves and mixing processes resulting from the interaction between turbulence and stratification. The first part of the study is applicable to the evolution of density step structures observed in the atmosphere and oceans, which consist of turbulent layers separated by density interfaces (Padman & Dillon 1989, J. Phys. Oceanogr., 18, 1458-1462). The second investigation is aimed toward parameterization of processes occurring at the oceanic convective layers, for example, the night-time boundary layer where cooling-induced convection plays a significant role in the generation of turbulence (McPhaden & Peters 1992, J. Phys. Oceanogr., 22, 1317-1329).

Approach:
The study on differential mixing was mainly laboratory experimental, supplemented by the development a phenomenological model based on prior studies related to entrainment from one side of the interface. The experiments were carried out by using a two-layer stratified fluid system of which the homogeneous layers were agitated by oscillating grids that generate unequal turbulent intensities; the interfacial migration rate and the properties of turbulent layers were measured. In the theoretical study on mixing and internal waves, the techniques of rapid-distortion theory were applied to calculate turbulent parameters (e.g., r.m.s. velocity and other integral properties) in and around a density interface forced by contiguous turbulent layers. Laboratory experiments were also carried out by subjecting density interfaces to grid-induced turbulence and the results were compared with the model predictions.

Tasks Completed:
In the first part of the study, the dependencies of the interfacial migration rate and buoyancy variations in the layers (and hence the buoyancy fluxes) were determined as a function of the governing system parameters. A simple model was developed to predict these parameters. In the second part of the study, a theoretical model was developed for the evolution of linear and non-linear waves on a thin thermocline (density interface) subjected to shear-free turbulence. The predictions of this model included various turbulence quantities and the interfacial mixing rate. State-of-the-art experimental techniques such as laser-

Doppler velocimetry and laser-induced fluorescence were used to measure the characteristics of the flow fields associated with thick and thin thermoclines.

Scientific Results:
The experimental results on interfacial migration rates in the presence of differential turbulence forcing were in general agreement with the phenomenological model developed as a part of the study (Figure 1). This model is based on the notion that the net interfacial migration velocity is the same as the resultant of entrainment velocities that occur when the opposite layer is non turbulent. Some discrepancies were noted, however, for which plausible explanations were provided. The interfacial migration occurs in a direction that opposes the gradient of inertia forces of the integral-scale turbulent eddies at the interface; it continues until the inertia forces on both sides have the same magnitude, whence the interface becomes stationary. Yet, the buoyancy transport though the interface continues and finally the system runs down to a homogeneous state. The results were recast, based on the properties of mixed-layer turbulence and density interface, into a form that is convenient for direct oceanic applications.

The model developed in the second part of the study was used to calculate the r.m.s. velocity fluctuations in and around a thin density interface, the r.m.s. amplitude of interfacial waves and the diapycnal-mixing rate. The agreement between the predictions and previous laboratory results was good. The present laboratory experiments with a thick density interface (sandwiched between a turbulent layer and a weakly stratified or an unstratified layer) revealed some interesting phenomena; a fourth, strongly stratified, layer was found to develop in the region between the thermocline and the turbulent layer, and most of the wave-turbulence interactions were confined to this layer. It had a velocity maximum, indicating the presence of many resonant modes of waves (Figure 2). Detailed measurements of the vertical velocity structure, internal-wave parameters and mixing characteristics pertinent to the density interface were made and, whenever possible, the results were compared with available theoretical predictions and geophysical observations.

Accomplishments:
A significant accomplishment is the demonstration of the sensitivity of diapycnal mixing to the interfacial Richardson number, in addition to the commonly used bulk Richardson number. The number of possible resonant internal-wave modes varies with the magnitude of the interfacial Richardson number and the energetics of mixing are dependent on the structure of internal waves. Also, we were able to obtain a simple bulk parameterization for entrainment in the presence of differential turbulent forcing, which can be applied in the studies of oceanic thermohaline staircase structures, for example, those described by Kelley (1987, J. Phys. Oceanogr., 17, 1633-1639).

** Figures will be sent to ONR **

ONR-Sponsored Publications

P- Noh, Y. and Fernando, H. J. S., 1993: The Influence of Molecular Diffusion on the Deepening of the Mixed Layer, Dynamics of Atmospheres and Oceans, 17, 187-215.
P- Noh, Y. and Fernando, H.J.S., 1993: A Numerical Model for the Fluid Motion at a Density Front in the Presence of Background Turbulence, Journal of Physical Oceanography., 23(6), 1142-1153.
P- Fernando, H.J.S. and De Silva, I.P.D., 1993: Note on

Secondary Flows in Oscillating-Grid Mixing Box Experiments, Physics of Fluids A , 5 (7), 1849-1851.

P- Fernando, H.J.S. and Ching, C.Y., 1993: Effects of Background Rotation on Turbulent Line Plumes, Journal of Physical Oceanography, 23, 2125-2129.

P- Fernando, H.J.S. and Ching, C.Y., 1993: Lead-Induced Convection: A laboratory Perspective, Journal of Marine Systems , 4., 217-230.

P- Lin, Q., Boyer, D.L. and Fernando, H.J.S., 1993: Note on Internal Waves Generated by the Turbulent Wake of a Sphere, Experiments in Fluids, 15, 147-154.

P- Noh, Y. and Fernando, H.J.S., 1993: The Transition in the Sedimentation Pattern of a Particle Cloud, Physics of Fluids A , 5 (12), 3049-3055.

PS - Davies, P.A., Boyer, D.L., Fernando, H.J.S. and Zhang, X., 1994: On the Unsteady Motion of a Circular Cylinder Through a Linearly Stratified Fluid, Philosophical Transactions of the Royal Society (London) , A345, 1-34.

PS- Ching, C-Y., Fernando, H.J.S. and Noh, Y., 1994: Interaction of a Negatively Buoyant Line Plume with a Density Interface, Dynamics of Atmospheres and Oceans (Accepted for Publication).

PS- Flor, J., Fernando, H.J.S. and Van Heijst, G.J.F., 1994: The Evolution of an Isolated Turbulent Region in a Two-Layer Fluid, Physics of Fluids (Accepted for Publication).

PS- Lin, Q., Boyer, D.L. and Fernando, H.J.S., 1994: Flows Generated by the Periodic Horizontal Oscillations of a Sphere in a Linearly Stratified Fluid, Journal of Fluid Mechanics (Accepted for Publication).

PS- Perera, H.J.S., Fernando, H.J.S. and Boyer, D.L., 1994: Turbulent Mixing at an Inversion Layer, Journal of Fluid Mechanics, (Accepted for Publication).

PS- Lin, Q., Boyer, D.L. and Fernando, H.J.S., 1994: The Vortex Shedding of a Streamwise-Oscillating Sphere Translating Through a Linearly Stratified Fluid, Physics of Fluids (Accepted for Publication)

PS- Perera, M.J., Fernando, H.J.S. and Boyer, D.L., 1994: Mixing Induced by the Oscillatory Flow Past a right Circular Cylinder, Journal of Fluid Mechanics (Accepted for Publication).

PS- DeSilva I.P.D. and Fernando, H.J.S., 1994: Oscillating Grids as a Source of Nearly Isotropic Turbulence, Physics of Fluids (Accepted for Publication).

PS- Ayotte, B.A. and Fernando, H.J.S., 1994: The Motion of a Turbulent Thermal in the Presence of Background Rotation, Journal of Atmospheric Sciences (Accepted for Publication).

PS- Fernando, H.J.S., van Heijst, G.J.F. and Fonseka, S.V., The Evolution of an Isolated Turbulent Region in a Stratified Fluid, Journal of Fluid Mechanics (under revision).

PS- DeSilva I.P.D. and Fernando, H.J.S., The Collapse of a Turbulent Mixed Region in a Stratified Fluid, Journal of Fluid Mechanics (under revision).

PS- Fernando, H.J.S. Migration of Density Interfaces Subjected to Differential Turbulent Forcing, Journal of Geophysical & Astrophysical Fluid Dynamics (under revision).

PS- Bermzn, N.S., Boyer, D.L., Brazel, A.J., Brazel, S.W., Celada, R.A., Chen, R-r, Fernando, H.J.S., Fitch, M.J., and Wang H-w. Synoptic Classification and the Design of Physical Model Experiments for Complex Terrain, Journal of Applied Meteorology (resubmitted).

PS- Davies, P.A., Mofor, L.A., and Fernando, H.J.S. Laboratory Studies of Mixed Buoyant Jets in Shallow Cross Flows, Transactions of the Institute of Civil Engineers, U.K (resubmitted).

PI- Fernando, H.J.S. and Hunt, J.C.R. Turbulent Mixing Across Shear Free Density Interfaces; Part 1 - Modeling Considerations.

PI- Fernando, H.J.S., McGrath, J. and Hunt, J.C.R. Turbulent

Mixing Across Shear Free Density Interfaces; Part 2 - Laboratory Experiments.
PI- Fernando, H.J.S., Mofor, L., Davies, P.A. and Ching, C.Y., Interaction of Multiple Line Plumes in an Uniform Environment.
PI- Fernando, H.J.S., Ching, C.Y. and Stegen, G.R., Some Aspects of the Evolution of Thermohaline Staircase Structures.
PI- Fernando, H.J.S., Ayotte, B.A. and Chen, R.-r., Turbulent Plumes in Rotating Fluids.
PI- DeSilva, I.P.D., Fernando, H.J.S., Montenegro, L. and Brandt, A., Laboratory Experiments on Instabilities in Stratified Shear Flows.
IC- Fernando, H.J.S., 1993: Stratified Turbulence: A Metaphor for Non-Equilibrium Complex Turbulent Flows. Invited Paper, ONR Workshop on Non-Equilibrium Turbulence, Mar 10-12, Tempe, AZ, 88-89.
C- Davies, P.A., Boyer, D.L., Fernando, H.J.S., and Zhang, X., 1993: Wake Flows in Stratified Fluids, Waves and Turbulence in Stratified Fluids, (Ed. S.D. Mobbs and J.C.King), 301-322, Clarendon Press.
C- Noh, Y., and Fernando, H.J.S. 1993: The Generation of Stratification in Shear Free Turbulence by an Imposed Buoyancy Flux, Near Wall Turbulent Flows (Ed. R.M.C. So, C.G.Speziale and B.E.Launder), Elsevier, 367-375.
C- Ayotte, B.A. and Fernando, H.J.S., 1993: Laboratory Studies Related to Open-Ocean Deep Convection. Ninth Conference on Atmospheric and Oceanic Waves, San Antonio, Texas, 249-251.
C- Berman, N.S., Chen R-r., Fernando, H.J.S., Boyer, D.L. and Celada, R.A., 1993: Combined Physical and Numerical Modelling for the Analysis of Wind Fields in Complex Terrain, Proceedings of the Speciality Conference on "The Role of Meteorology in Managing the Environment in the 90's, VIP-29, Air and Water Management Association, Pittsburg, PA, 296-303.
C- Fernando, H.J.S., Davies, P.A., Ayotte, B.A., Mofor, L.A. and Ching, C.Y., 1993: Turbulent Plumes, Thermals and Convection in Oceans, NATO Advanced Research Workshop on "Recent Advances in the Fluid Mechanics of Turbulent Jets and Plumes", Vianna do Castello, Portugal, Kluwer Academic.
C- Etling, D. and Fernando, H.J.S., 1993: On the Influence of Background Rotation on Turbulent Jets, NATO Advanced Research Workshop on "Recent Advances in the Fluid Mechanics of Turbulent Jets and Plumes", Vianna do Castello, Portugal, Kluwer Academic.
C- Ayotte, B.A. and Fernando, H.J.S., 1993: Laboratory Studies Related to Open-Ocean Deep Convection, Am. Geophys. Union, Ocean Sci., EOS, 74(16), 18.
C- Fernando, H.J.S., 1993: Migration of Density Interfaces Subjected to Differential Turbulence Forcing, Bull. Am. Phys. Soc., 38(12), 2254.
C- Ching, C.Y. and Fernando, H.J.S. 1993: The Interaction of Turbulent Line Plumes, Bull. Am. Phys. Soc., 38(12), 2253.
C- DeSilva, I.P.D., Montenegro, L.M., Mavrikos, N., Fernando, H.J.S. and Brandt, A. 1993: Experiments on Kelvin-Helmholtz Instabilities in Stratified Shear Flows, Bull. Am. Phys. Soc., 38(12), 2254.

Statistics
7 Papers published, refereed journals
14 Papers submitted, refereed journals
6 Books or chapters published, refereed publication
0 Books or chapters submitted, refereed publication
1 Invited presentations
4 Contributed presentations
0 Technical reports and papers, non-refereed journals
1 Undergraduate students supported
0 Graduate students supported

1 Post-docs supported
0 Other professional personnel supported

EEO/Minority Support
0 Female grad students
0 Minority grad students
0 Asian grad students
0 Female post-docs
0 Minority post-docs
1 Asian post-docs

Patents and awards
The PI was appointed as the Director of the Environmental Fluid Dynamics Program at Arizona State University.

Influences:
The results of our work have been requested by and transmitted to Dr. Patrick Gallacher of the Naval Research Laboratory and Dr. David Johnson of the Office of Naval Research for the purposes of modeling and interpretation of field observations. In addition, we have interactively worked with personnel of the Science Applications International Corporation in adapting our stratified turbulent shear flow results to oceanic dispersion problems, especially the discharge of Carbon Dioxide to deep ocean and its subsequent mixing by small-scale turbulence.

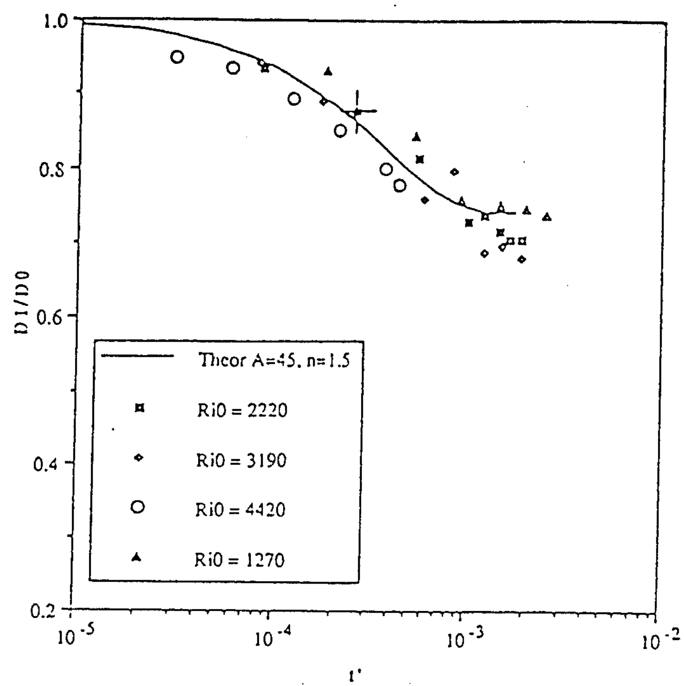

Figure 1: A comparison of the model prediction (dark line) with the experimental results (symbols), for the case of differential turbulent forcing on a density interface. The variation of the non-dimensional interfacial position (D1/D0) with non-dimensional time (t') is shown. Here the ratio of eddy diffusivities of the upper and lower layers is 0.5; D1 represents the depth of the upper layer and D0 is its initial value. Ri0 is an initial bulk Richardson number. The constants A1 and n are based on the case where turbulence is present only on one side of the interface.

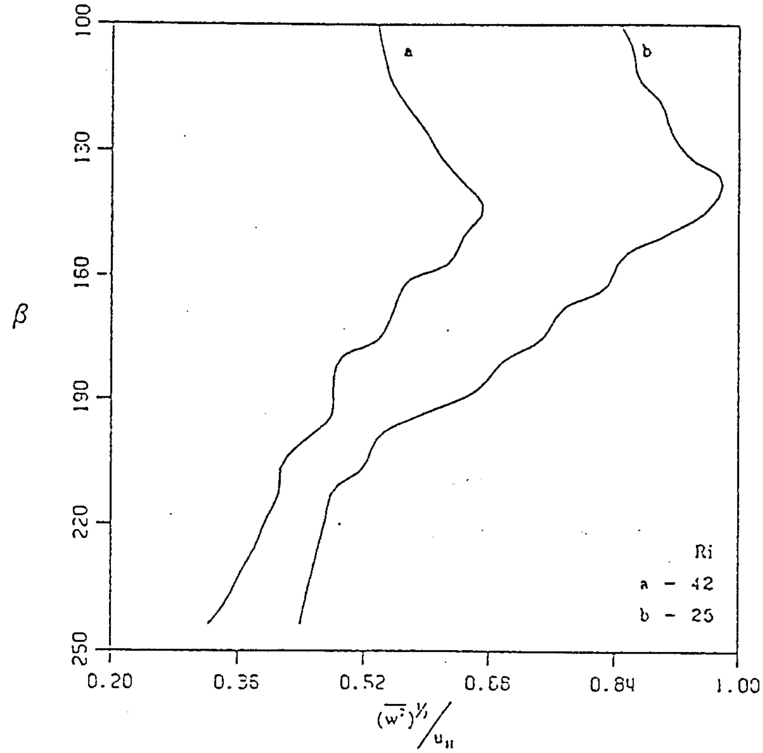

Figure 2: The variation of the normalized r.m.s. vertical velocity within a (thick) density interface, for the case where the interfacial Richardson number (based on the interfacial thickness) $Ri_I > \pi^2$. A velocity maximum can be seen within the interface. In the case of a thin interface with $Ri_I < \pi^2$, only the first mode of internal waves is present and the velocity profile is flat. This shows that, in calculating diapycnal fluxes, Ri_I should be considered along with the usual bulk Richardson number Ri. β is indicative of the vertical position within the interface.